Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-68367-8

Detection of imperfections in diaphragm walls with geophysical measurements

R. Spruit
Rotterdam Public Works, Engineering Department, Rotterdam, The Netherlands
TU Delft, Delft, The Netherlands

V. Hopman
Deltares, Delft, The Netherlands

A.F. van Tol
Deltares, Delft, The Netherlands
TU Delft, Delft, The Netherlands

ABSTRACT: After calamities with leaking diaphragm walls in Amsterdam and Rotterdam the caution to use diaphragm walls in deep excavations in the Netherlands increased. In densely populated areas the risk of unanticipated and uncontrollable leakage and the following subsidence is not acceptable. In autumn 2009 a joint research project was initiated at Rotterdam Public Works and TU-Delft aiming at development of a system of measurements and interpretation to detect zones in the diaphragm wall with high risk of leakage. The research started with a series of in-situ tests. Four types of measurements (distributed temperature during pouring and hydration of the concrete, natural gamma radiation, cross hole seismic and direct resistivity between the rebars and a conductivity CPT) were executed on 5 test panels and 2 laboratory size blocks. In this paper the results from the measurements are presented. Preliminary conclusions on how to set up a survey are drawn. An outlook into the further progress of the research will be given.

1 INTRODUCTION

Traditionally, diaphragm walls were considered a safe and proven technology for constructing the wall of a deep excavation. Due to recent uncontrollable leakages occurring in metro building projects in Amsterdam and Rotterdam (Netherlands), the risk profile of the diaphragm wall has changed.

As there is a clear need to reduce the uncertainty of the quality of in-situ formed construction elements, a research has been started to determine if areas with a high risk of leakage can be detected before excavation takes place. From December 2009 till May 2010, instrumentation and testing took place on site and on laboratory scale.

Like in borehole geophysics, it was assumed that the combination of several tests will lead to a reliable conclusion. Therefore, four different measurements were carried out.

2 TEST LOCATION

Underneath the 'Kruisplein' in the center of Rotterdam a 6 stores underground parking facility is being constructed. Diaphragm walls to a depth of 40 m minus surface level (at which level a clayey layer with high hydraulic resistivity is present) will ensure a robust and watertight ground retaining construction.

Several measures to improve the quality of the diaphragm walls were included in the contract. To reduce the uncertainty of the final build quality, the hydraulic resistance of the wall is also tested by lowering the water table inside the building pit.

Still, in case of bentonite inclusions in the joints between the diaphragm wall panels, potential weak spots in the wall will not be found in the pumping test, as the bentonite inclusion has a high hydraulic resistance and will therefore prevent water inflow through the diaphragm walls. During excavation however, the bentonite inclusions may become instable, due to the change in horizontal ground and water pressure. After gradual degradation of the bentonite inclusion a sudden major leak can occur, resulting in large volumes of water and (possibly) sand flowing into the building pit. If transport of sand occurs, subsidence outside the building pit will occur, causing damage in case of to neighboring buildings and infrastructure.

It was therefore thought worthwhile to investigate the possibilities to detect bentonite inclusions prior to excavation. Measurements on site and on laboratory scale were performed.

3 DESCRIPTION OF THE TESTS AND RESULTS

3.1 *Temperature*

During fabrication of a diaphragm wall panel the volume in the excavated trench is being replaced several times. After reaching the final depth with the excavator the excavation bentonite has to be replaced by fresh (lighter) bentonite which in the next stage has to be replaced by concrete. Each material has a specific temperature when entering the trench. By using a vertically positioned distributed temperature measurement, it is possible to keep track of the different materials in the trench. The temperature has been measured with optical fibers (Del Grosso et al. 2001). With a Sensornet Oryx DTS (Sensornet 2009), the temperature distribution along the fiber could be measured. The temperature accuracy is around 0.01 °C whereas the accuracy of the position of the measurements is 1 m. The fibers were positioned as indicated in Figure 1.

As it is assumed that most problems occur around the joints, the temperature sensors were positioned as close to the joint as possible. One fiber was attached to the rubber joint profile, another fiber was connected to the rebar grid and finally a fiber was lowered into the joint area using a metal weight at the bottom end of the fiber.

The temperature measurements started after the reinforcement cages were positioned and continued until one week after the concrete was poured into the trench. Every 20 minutes a measurement cycle was performed, clearly showing the rising concrete level in the trench because the temperature of the concrete was with 17 °C higher than the temperature of the bentonite with 13 °C (Fig. 5).

During curing of the concrete the temperature rose in 55 hours from 15 °C to 35 °C (Fig. 2).

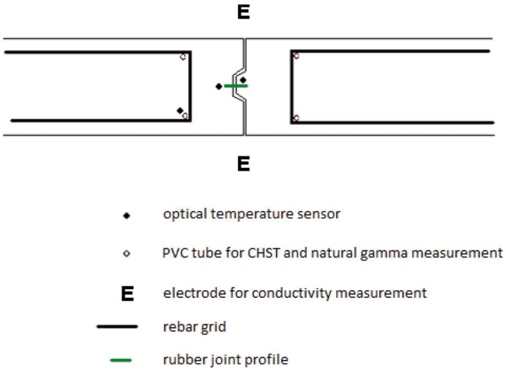

Figure 1. Top view of the location of the sensors around a diaphragm wall joint.

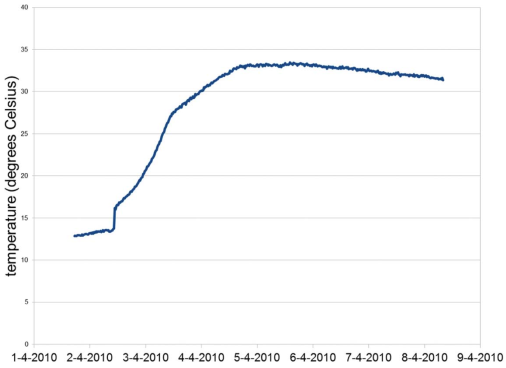

Figure 2. Temperature development in the next joint.

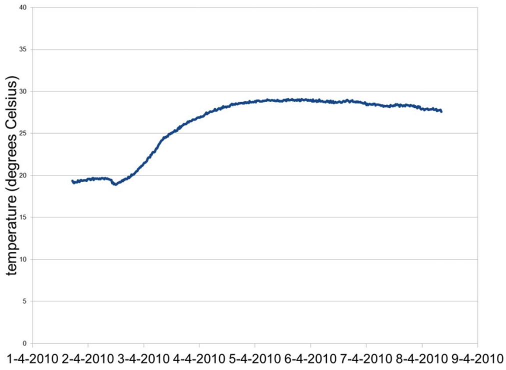

Figure 3. Temperature development in the previous joint.

Figure 3 shows that along the joint with the previous panel (previous joint, concrete 1 week old), the temperature of the bentonite in the joint is around 20 °C. When the concrete level approaches, a slight drop of around 1 °C–2 °C occurs, possibly indicating stirring of the bentonite and/or replacement of bentonite for concrete. When this drop in temperature consistently occurs along the vertical profile of the wall, it seems plausible that (almost) no bentonite has stayed behind in the joint.

In Figure 4 at sensorposition 88, all subsequent temperature measurements show 19 °C, possibly indicating an area where bentonite stayed behind in the joint.

On the sensor along the next joint, the steady change from bentonite temperature to concrete temperature indicates a decent joint. This is illustrated in Figure 5.

At position 110 in Figure 5, a slight delay in the concrete pouring process can be seen. As each line indicates a measurement 20 minutes later, the 2 almost identical measurements at position

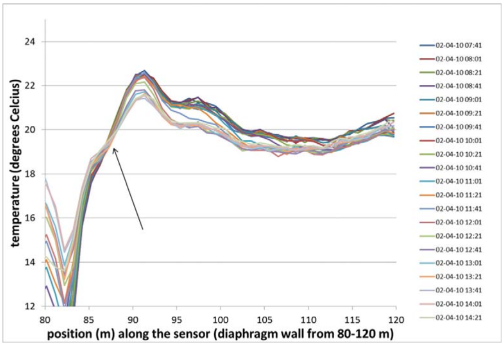

Figure 4. Temperature graph in the previous joint.

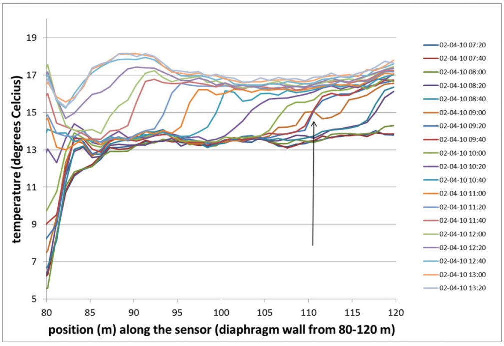

Figure 5. Temperature profile during concreting.

110 indicate a stop of 20 minutes during the concrete pouring.

In the laboratory test, the temperature measurements were less convincing, partly due to the more rapid pouring of the concrete (the laboratory block was only 2*2*1 m^3 instead of 42*6*1.2 m^3) and partly because of the spatial resolution of the temperature measurement of 1 m.

3.2 *Natural gamma radiation*

Normally, clay minerals tend to have a higher natural radioactivity than the ingredients of concrete. It was therefore assumed that areas with high amounts of bentonite remaining in the trench after the pouring of concrete might be detected by measuring the natural radioactivity. Using a gamma ray detector, the radiation along the joint was measured, using the PVC tubes indicated in Figure 1.

Unfortunately, the natural radioactivity of the concrete came out to be higher than the radioactivity of the bentonite. Even with a gamma spectrometer no detectable differentiation between bentonite and concrete could be made.

Table 1. Radioactivity of concrete and bentonite as determined using samples originating from the site.

Specimen	^{40}K (Bq/kg)	^{232}Th (Bq/kg)	^{238}U (Bq/kg)
Concrete	215	20	30
Bentonite (dry)	160	12	15
Bentonite (wet)	107	9	7

As it will be almost impossible to detect a small amount of material in the joint with a relatively low radioactivity when the majority of the material has a relatively high radioactivity, this detection method can only be used if the concrete mixture consists of especially selected materials with low radioactivity.

3.3 *Cross-hole seismic tomography (CHST)*

The speed of sound in a solid medium is depending on the density and the shear stiffness. Because concrete and bentonite have a different density and shear stiffness, it must be possible to discriminate between concrete and bentonite using an acoustic signal. By attaching PVC tubes on the rebar cages on both sides of the joint (Fig. 1), it is possible to send an acoustic signal across the joint.

This method is already commercially available for testing the integrity of large diameter bored piles (Amir et al. 2008). In the test we used the CHUM equipment of PileTest (PileTest 2009).

In advance it was unknown what influence the joint would have on the signal transmission as there is little experience in similar situations.

In literature (Likins et al. 2004, Amir et al. 2008) different opinions on the tube material to be used were found. For robustness and better bonding with the concrete, steel tubes should be chosen. In PVC tubes the signal seems to contain less noise. Debonding of the PVC tubes from concrete seems unlikely when the tubes are filled with water (Likins et al. 2004).

As the reinforcement cages were not prepared for the tubes, they had to be retrofitted. PVC tubes are much easier to handle than steel ones. Therefore 14 out of the 16 tubes we chosen PVC, the 2 remaining ones were chosen steel, making it possible to compare the different materials.

The measurements on site could be performed very fast especially considering the 42 m wall depth. Within 30 minutes all 6 cross-hole combinations could be measured. This is the time needed for the simple 'horizontal' measurement in which both source and receiver are on the same level and are pulled up simultaneously. Theoretically it is also possible to vary the source/receiver position in such a way that 2D tomography is performed. In the signal there was generally no hint for the need of this extra measurement density.

Only in one joint an anomaly was found. At the depth at which this anomaly was found, clayey layers are expected outside the excavation. Therefore no further measures are taken to prevent leakage as the soil itself functions as a barrier. As excavation is still in progress no verification of the size of the anomaly can be made yet.

In Figure 6 the anomaly at 8–9 m minus surface level can clearly be seen. The upper 4 m consists of low grade concrete due to pollution with bentonite.

From the laboratory tests (Fig. 8) a first indication of the anomaly size can be deducted. The test blocks were poured in a normal formwork with a steel joint profile as the lower boundary of the formwork. After curing of the first half, the block was inverted, an anomaly was sculptured in the joint area, the formwork was attached again and the upper block was poured. Instrumentation was set up similar to the in-situ tests.

A typical CHUM graph from the test blocks is shown in Figure 7. The known anomaly is present from 0.1 m to 1 m and varies in thickness from 0 to 0.3 m.

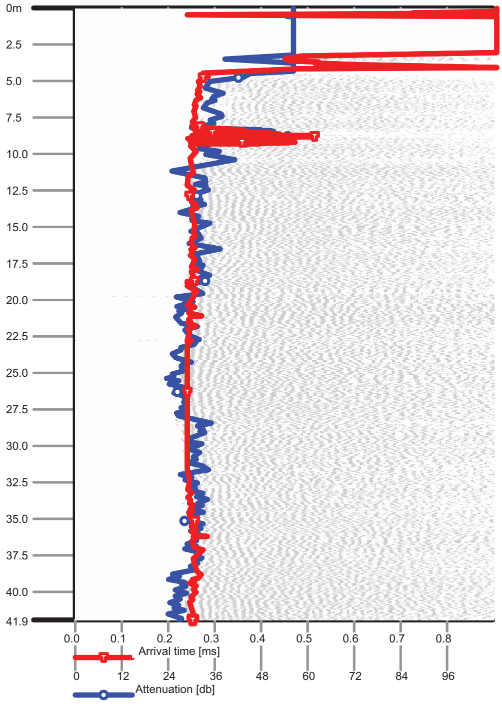

Figure 6. Cross-hole seismic profile.

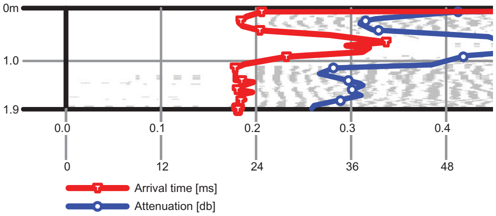

Figure 7. Typical CHST profile of the laboratory block, straight across the joint.

Figure 8. Laboratory block.

The average (from two test blocks) extra arrival time for a joint contaminated with 0.3 m bentonite is straight across the joint 0.23 ms and 0.35 ms diagonally across the joint. Because the ‘straight’ signal can partly bypass the inclusion, the expected extra travel time will be around 0.1 ms per 0.1 m bentonite inclusion.

The average damping of the signal is 20 dB for a joint with 0.3 m bentonite. 7 dB damping per 0.1 m bentonite is expected.

The anomaly found in the in-situ profile of Figure 6 shows 0.25 ms extra arrival time combined with 24 dB damping. If the laboratory samples prove to be representative, the size of the anomaly could be in the order of 0.25 m (based upon arrival time) and 0.35 m (based upon damping). When we combine the extra arrival time with the damping, we expect around 0.3 m of bentonite in the joint. In October the excavation will reach the anomaly. As the anomaly was only found in the cross section of the side to be excavated, we expect to get an in-situ confirmation of the laboratory tests.

3.4 *Resistivity*

Based on the principle that solid concrete has a high electrical resistivity (compared to soil), it is expected that an imperfection in the joint could be made visible in an electrical resistivity measurement along the joint (Hwang et al. 2007). For this measurement a reference electrode (steel rod) was pressed into the soil with a CPT truck outside the building pit. With a resistivity cone attached to the CPT truck, an electrode was gradually pressed into the soil inside the building pit.

The local electrical soil resistivity was measured with the CPT cone (CONE in Fig. 9), the electrical resistivity from the cone to the reference electrode outside the building pit was measured (REF in Fig. 9) as well as the resistivity between the cone and the rebar grids on both sides of the joint (RBG_N, RBG_S in Fig. 9).

The resistivity profile was measured at the same joint as the CHST profile of Figure 6 in which an anomaly was detected at 8 to 9 m minus reference level. In Figure 9, at the same depth, there is a 30% (relative to the average 1 MOhm resistance) decrease of the resistivity over the diaphragm wall (REF in Fig. 9). The resistivity from the cone to the rebar grid north of the joint (RBG_N in Fig. 9) also shows a slight dip in resistivity. It can therefore be concluded that there probably indeed is an anomaly at this depth, only occurring in the panel north of the joint. The anomaly probably reaches to 1/3 of the wall thickness, based upon a decrease of the resistivity of 30%.

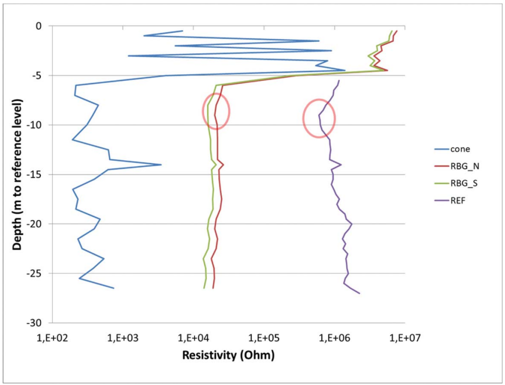

Figure 9. Resistivity profile.

3.5 *Interpretation*

When the information of the resistivity measurement is combined with the CHST profiles of the same joint, which show only defects in one profiles out of six it is concluded that:

- there will probably be a defect on the side of the excavation with rough dimensions of 1 m high, 0.3 m wide at the maximum (from CHST measurements).
- the defect will probably extend 0.4 m into the wall (1/3 of 1.2 m) and will be only present in the panel north of the joint (from resistivity measurements).
- the temperature measurements of this specific joint (Fig. 4) do not clearly show a drop in temperature during the pouring of the concrete, especially at the depth of the anomaly found in figure 6 which is an extra indication that a bentonite inclusion could be present.

4 CONCLUSIONS

The measurements performed on the ‘Kruisplein’ location in Rotterdam as well as in the laboratory generally improved our understanding of the concrete pouring process of diaphragm walls.

The natural gamma radiation measurement did not function as intended as a result of the high natural radioactivity of the concrete. In case the ingredients of the concrete are screened on low radioactivity, this method could be useful.

The temperature measurements might be used to monitor the efficiency of the refreshing of the bentonite mixture prior to the concrete pouring. During the pouring of the concrete, the process in which the bentonite is replaced by concrete can be monitored. With the distributed temperature measurement it is already in the production stage possible to indicate areas that have a higher chance of showing defects.

The CHST measurements proved to provide detailed information about the quality of the joint. Using the first reference information of the laboratory blocks, it is possible to estimate the volume of the anomaly that was found in the test area. Exposing this anomaly later in the project during excavation of the building pit will provide additional reference material.

The resistivity measurements proved to be useful for investigating the depth into the wall of an anomaly and helped indicating on which side of the joint the anomaly is located.

Further investigation of the temperature measurements will focus on the best location and interval (in time) for the measurements to be performed.

Further investigation on the CHST method will focus on the change in signal (frequency domain) during passage of the joint. The change in stiffness from concrete to the material in the joint might be visible as a change in the characteristics of the signal, providing extra information about the contents of the joint material. Also additional reference measurements will be performed.

Further investigation of the resistivity measurement will focus on the improvement of the measurement setup, as to reduce operating time in the field and at the same time improving resolution.

ACKNOWLEDGEMENTS

The tests were cofounded by the Municipality of Rotterdam and the contractor Besix/Franki. Some of the measurements were sponsored by Deltares, Medusa Exploration, Gemeentewerken Rotterdam-VLG, Fugro and Brem.

REFERENCES

Amir, J.M. & Amir, E.I. 2008. Capabilities and Limitations of Cross Hole Ultrasonic Testing of Piles; http://www.piletest.com/papers/IFCEE2009.Capabilities_and_Limitations_of_Cross_Hole_Ultrasonic_Testing_of_Piles.pdf.

Del Grosso, A. & Inaudi, D. 2001. Monitoring of Bridges and Concrete Structures with Fibre Optic Sensors in Europe; http://195.186.87.221/Bibliography/PDF/C92.pdf.

Hwang, R.N. & Ishihara, K. & Lee, W.F. 2007. Forensic Studies for Failure in Construction of An Underground Station of the Kaohsiung MRT System; http://civil.iisc.ernet.in/~gls/Courses_files/FORENSIC%20GEOTECHNICAL%20ENGINEERING.pdf.

Likins, G. & Webster, S. & Saavedra, M. 2004. Evaluation of defects and tomography for CSL; http://www.pile.com/reference/stresswave2004/SW2004-046-Eval_of_Defects_and_Tomography_for_CSL.pdf.

PileTest 2009. http://www.piletest.com/show.asp?page=chum.

Sensornet 2009. http://www.sensornet.co.uk/news/product-literature/.